DETONATORS AND DETONATION

By

WARREN DAVIS CALHOUN

LT. U.S.NAVY

Thesis
C188

Library
U. S. Naval Postgraduate School
Annapolis, Md.

DETONATORS AND DETONATION

by

Warren Davis Calhoun

A THESIS
Presented to the Graduate Faculty
of Lehigh University
in Candidacy for the Degree of
Master of Science

Lehigh University
1950

Thesis
C108

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

ACKNOWLEDGMENT

I wish to thank Dr. W. O. Snelling, of the Trojan Powder Company, Allentown, Pa., for his help in finding material and his ideas as to presentation of the material used. I also wish to thank Dr. Warren W. Ewing for his help in reading my thesis.

TABLE OF CONTENTS

Page

Introduction
Theory of Detonation. 4
"Explosive Wave" Theory 4
Breaking Theory 8
Strength of Detonators. 22
TNT-Iron Oxide Insensitive Test 24
Sand Test 25
Lead Plate Test 28
Trauzl Lead Block Test. 32
Miniature-Cartridge Test. 36
Types of Detonators 38
Fuse Detonators 38
Electric Detonators 40
Delay Electric Detonators 45
Conclusion. 48

INTRODUCTION

An explosive substance may be defined as a chemical system which may, when subjected to a suitable initial impulse, undergo nearly instantaneous chemical decomposition or transformation, with evolution of heat and formation of decomposition products, some of which are gaseous. In an explosive reaction, there is always a sudden rise of pressure, due to the formation of gases and to their expansion by the heat liberated in the reaction.

There are included in explosive substances, a wide range of mixtures and of homogeneous chemical compounds. In general, the explosive reactions to which they give rise are characterized either by an extremely rapid combustion, or by a rearrangement of molecules, which proceeds practically instantaneously.

In explosives for which the reactions are rapid combustion, oxygen is always present with one or more combustible elements. The oxygen is supplied in such form as to permit the oxidation or combustion to proceed without support from outside sources. This type reaction is true burning, which proceeds from point to point throughout the explosive, accelerated by the heat

and pressure produced. These explosives are, therefore, known as burning explosives, or low explosives. Of this type, black powder and smokeless powder of various classes are typical.

In explosives for which the reactions are the rearrangement of molecules proceeding practically instantaneously, oxygen is nearly always present, with combustible elements such as carbon and hydrogen, being usually held in the system in weak bonding radicals, most frequently in the nitro group. In these explosives, the chemical arrangement is one of unstable equilibrium and the initial impulse brings about a breaking down of chemical bonds and a rearrangement of molecules which is so rapid that the evolution of heated gaseous products is practically simultaneous throughout the mass. Such explosives are known as DETONATING or HIGH explosives. Oxygen is not an essential part of all detonating explosives. For example, the metallic azides, or metallic salts of hydronitric acid, such as lead azide, which contain no oxygen, are detonating agents. Most detonating explosives, such as are used for the main charge in torpedoes, mines and high explosive projectiles, as well as in many forms of blasting, require for initiating

their action the sudden application of a very strong shock, such as is given by the detonation of another charge in contact with or in close proximity to them. This impulse is usually supplied by a sensitive detonating substance, such as fulminate of mercury and its mixtures, which can be detonated readily by the application of heat.

The devices used to initiate detonation in larger charges are called detonators. In many forms of detonating charges, there is an intermediate charge or booster, between the detonator and the main charge. The booster charge contains more explosive than the detonator but is small as compared with the main charge.

The field of explosives has advanced considerably over the years since the work of Nobel. Along with the development of better explosives came the necessary work and development of detonators and their effectiveness.

Theory of Detonation

In the study of the theory of detonation, you are faced with the problem of studying a field of science of explosives that has not been completely investigated. Many theories have been brought up along with the experimental or mathematical evidence to support the idea under investigation. A few of the more interesting ones, when analyzed in part and combined with others, shed some light on the phenomenon we know as detonation.

Berthelot's "Explosive Wave" Theory (3)

In order to analyze the propagation of an explosive wave, the wave is considered as a recurring cycle of released and transformed energy with four phases: Mechanical to calorific, calorific to chemical (the phase in which the potential energy of the explosive material is released), chemical to calorific, and calorific to mechanical.

This cycle can be readily understood by indicating how the explosive wave is propagated through a cylindrical column of a homogeneous explosive without the loss of enough energy to interrupt propagation. Transformation of Mechanical Energy to Calorific Energy:

When an explosive detonates, a part of the mechanical energy of a layer of the explosive is converted instantly into heat energy in the adjacent layer by reason of the impact of molecules. The effecience of this conversion is low--certainly less than 50%--as the movement of the molecules is radial and they are only partly confined by the layer of explosive in the column. The mechanical energy that is not converted into heat energy exerts pressure on the confining medium and thus becomes the vehicle through which work is accomplished. There is good reason for believing that the thickness of the layer of explosive that enters into the first phase of the cycle varies with the physical properties of the explosive material, principally with its elasticity and partly with the velocity of the molecules that are in molecular vibration. The less elastic the explosive material and the greater the velocity of the molecules, the thinner the layer, and hence the more times the cycle will recur in a unit length of the explosive material.

Transformation of Calorific Energy to Chemical Energy:

Some of the calorific energy of the layer is used to overcome the chemical stability of the explosive material, which may vary widely, and thus release the

potential energy of the layer; the rest of the calorific energy is used to accelerate and reinforce the chemical action. The layer of explosive by this time is developing a tremendous kinetic energy as is shown in phase three.

Transformation of Chemical Energy to Calorific Energy:

All explosives develop heat on detonation. This phase is different from the others because each of those represent some kind of kinetic energy derived entirely from the preceding phase, and consequently no one of them can have more kinetic energy than the preceding phase is capable of transferring. The conversion in this phase is complete because all the potential energy released becomes kinetic energy, which is largely calorific energy.

Transformation of Calorific Energy to Mechanical Energy:

A simple statement of this phase is that the larger volume of gases then formed from the layer of explosives is in an extremely active state of molecular vibration and that these molecules are then manifesting their energy as mechanical energy. The efficiency of conversion of caloric energy to mechanical energy is high because the conversion is very rapid.

If heat, such as is produced by the physical resis-

tance of the explosive to a blow or impact, be applied indirectly to high explosives, then any sufficient blow or impact will cause detonation; that is, it will initiate the four-phase energy cycle or explosive wave.

This theory was devised about 1865 and is still used in part to explain many phenomona of detonation.

In further investigation of the theory of detonation, one finds numerous and varied experiments on many different phases of the subject.

The crystallographer presents his ideas and tries to prove what the crystal structure of explosives has to do with detonation. A view expressed in paper by M. Veron in 1938, stated that he had a new theory. From his experiments, he found that detonation appears always at the end of deflagration and immediately after the maximum pressure has been attained by the gas. He stated that he thought the detonation was caused by very high pressure at the beginning and rapidly increasing pressure at the end of the deflagration.

An experiment by Hamon and Woodhead in 1937, showed that the expansion of the disturbance produced when a cartridge of high explosive, suspended freely, is detonated, occurs in three phases: (1) the initial phase

has an almost spherical form, arising from the sides of the cartridge; (2) the second phase lasts until the disturbance has travelled 100-125 cm. The gaseous products are at first mostly luminous, and follow the shock wave at a gradually increasing distance. The greater expansion from the ends of the cartridge causes axial distensions of the wave, accentuated by a shower of solid particles. The gases then lose their velocity as they mix with air; (3) the wave becomes smooth again and spherical in form, losing velocity until it degenerates into a sound wave. This experiment gives a physical picture of what occurs in a detonation but adds very little to the knowledge of the theory.

Kinetics of crystal growth and decomposition was analyzed by W. E. Garner in 1935. He showed the nuclear growth in decomposition is considered as a branching structural chain reaction. The conclusion reached was that the origin of detonation in solids is not a simple thermal effect, but depends on the crystal structure. This experiment is one more of the many that supply one small part to the overall picture of detonation.

The Breaking Theory of Detonation - Leroy Earl (4)

This theory is one of the more recent ones and

seems to cover more of the aspects of the theory of detonation than many. Carl attempts in a straight forward way to postulate a complete theory. Before actually reviewing this theory, it is well to briefly look at a few interesting facts about well known chemical and physical phenomena that Carl uses for ground work to build his theory on.

Carl takes exception to the statement of Berthelot that:

"Every explosive reaction should be attributed to a preliminary heating, which is gradually transmitted directly or indirectly, raising successively all the parts of the matter to the temperature of decomposition, shock, pressure, friction or mechanical effects are only efficacious by causing this preliminary heating". (3)

There are three points of Berthelot's theory that the breaking theory tries to disprove. They are:

(a) In every case of explosion, there must be a preliminary heating, which is the means of initiating and transmitting the detonation.

(b) The same mechanism is involved in detonation of gases, liquids, and solids.

(c) The velocity is not thought to be determined by the physical nature of the material.

There are outstanding differences between gases, liquids and solids; the great compressibility of gases as compared to the slight compressibility of liquids and solids. Another difference is the fact that solids have rigidity of shape and even liquids have an instantaneous rigidity of shape.

Examples of effect of physical condition are shown by Coates and Perrot (5) in tests of gelatin dynamites, containing nitro-glycerine and ethylene glycol dinitrate. These samples were fired after various periods of storage, both in the confined and the unconfined condition, with and without priming charges of straight dynamite, yet in almost every case, the rate of detonation, after storage, was definitely much less than that of the original samples. Here is an example of chemically identical material showing different rates of detonation because of physical change.

Many still consider the rate of detonation equivalent to the rate of reaction. Hayes (6) says:

"The rapidity of reaction of an explosive may be determined directly, by experiment, in high explosives. This is termed the rate of detonation of the explosive, and is a measure of its brisance".

From Berthelot's conclusion that other things being

equal, the sensitiveness of explosive substances is the greater the more heat developed by the explosive reaction, seems to be untrue. Most of the very sensitive compounds are low in total energy. It seems that no two characteristics of any explosive can be correlated. No property connotes any other property. Carl brings out that a high rate of detonation does not guarantee a high total power or shattering effect; nor great sensitivity; also low ignition temperature does not indicate high sensitivity to other means of initiation.

It is Carl's belief that there is a complete lack of consistency in all the data concerning high explosives. The lack of consistency seems to be due in part to the fact that no theoretical basis for experimentation has been developed.

For the ground work of this new "Breaking Theory of Detonation", knowledge of crystal structure, strength, and rupture is useful. From X-ray study the regularity of the crystal lattice was revealed by Bragg in his experiments. The molecule has definite structure; a framework connected by valence forces which are directional and the crystal may, for many considerations, be treated as one large molecule.

From the experiments of researchers on the strength

of the crystal and the nature of rupture, Joffe (7) says:

"The tensil strength of single crystals is almost 500 times less than the calculated maximum for the cohesive forces and rupture occurs before an essential deviation from Hook's law can be noticed".

Joffe finds that rock salt crystals become plastic when immersed in hot water and exhibit strength up to 160 kg per sq. mm. As compared to a strength of .5 kg. for the ordinary condition. He suggests as a possible hypothesis the existence of very small crevices in the surface which would cause the entire load to be exerted on a point instead of on the whole cross-section.

Bridgman (8) states that the:

"Fracture occurs in a body when the external conditions are altered if all the atoms cannot find new positions, not far from the original positions, in which they will still be subject to zero net force on the average".

From several other experiments conducted, such as a hard rubber ring broken by hydrostatic pressure, showing that the break was against the direction of the stress, the distortions in molecular arrangements which are effective,

and the fact that every distance between molecules has been shortened absolutely at the moment of rupture. These facts do not seem consistent with theory. Breaking seems to be not as simple a subject as at first it would appear.

In some crystals there is an internal force inherent in the structure of the crystal, which tends to displace the valence forces from their normal direction. This condition exists in endothermic or unsaturated compounds. Unsaturation indicates a looseness of structure and lack of stability. The properties of many unsaturated organic substances follow the 'strain theory' of Bolger. This theory states that a bond tends to lie in a straight line joining atom to atom, and the directions of the four bonds emanating from a single carbon atom are those determined by tetrahedral symmetry. Whenever these bonds are forced out of these positions, there is supposed to be a state of strain which manifests itself through instability and general characteristics of unsaturation.

This internal strain accounts for the energy released by the endothermic compounds when they break down, and shows up as heat when unsaturated compounds burn. As an example, when a compound like ethene burns

to carbondioxide and water, the calories developed is less than the number developed by the combustion of the elements that make up the methane molecule. When acetylene burns, the heat produced far exceeds that produced by combustion of an equivalent quantity of the constituent elements. The difference is found to be, in the first case, in the energy required to break the valence bonds; and in the second case, the energy given off when internal strain is released. From Henrich (9)

"In interpreting these facts, it is necessary to assume not that energy is required to break the double bond between the carbon atoms, but that energy is actually set free during this process. This difference has been explained by supposing that a certain degree of tension is developed within the molecule by the union of the second pair of valencies of carbon to form a double bond, and that such an atomic arrangement must, therefore, be regarded as representing a definite amount of stored up chemical energy. If the equilibrium in a system of this kind is disturbed in any way, the energy is set free. Thus, in the process of burning, it appears as heat and serves to increase the total heat of combustion of the substance".

Some systems, when slightly disturbed, may revert back to the same state of rest, while others, if largely disturbed, may proceed toward some entirely new condition of equilibrium. Energy required to release a crystal from its original form may vary with different compounds, from a rather large magnitude to zero as a limit, and so with the endothermic compound, its stability may approach zero as a limit. A good example of this is nitrogen iodide, which is stable when kept under water, but explodes spontaneously when dry. This endothermic condition is found in most initiators of detonation, and is probably a most important prime condition for such agents. A sudden disturbance of a crystal or part of a crystal, such as breaking, may allow the strain to disappear with the velocity of sound, and thereby transmit the disturbance to surrounding crystals.

With the knowledge of the material just presented, the Theory of Detonation proposed by Leroy Carl may be examined with some understanding.

This theory states that detonation is the progressive breaking of the valence bonds of a material, by a stress which is transmitted through the material as an

elastic wave, similar to a sound wave. This sound wave is of such intensity as to destroy the structure of the material. There is some distinction between this type of wave and an ordinary sound wave, the particles have a to and fro movement, whereas, in this type of wave in detonation, there is no return motion of the particles carried forward by the wave, because of the collapse of the material, by the extremely high pressure produced behind the crest of the wave, and by the recombination of the elements which had constituted the explosive.

The ability of a material to transmit this stress will depend upon the elastic nature of the material. The optimum condition for the transmission of the breaking wave is a material which is perfectly elastic, and which requires only a slight distortion to cause a breakdown. Thus, it is seen a perfect crystal supplies the nearest approach to these qualities. Materials which are soft, plastic or fluid, tend to damp out elastic waves and have a similar tendency with detonation.

The energy associated with this breaking wave is created by the release of gases and heat; this maintains the wave as a continuous compression instead of a com- [illegible]

pression and a rarifaction of the ordinary sound wave.

The source of such energy may be the release of strains already existent in the materials; nevertheless, some assistance from an outside force is usually required. Most initiating or primary detonating compounds belong to this class. They are rare materials which are absolutely necessary for the utilization of the common high explosives. The initiating impulse for this type of compound, may be a rise of temperature, impact, friction, the breaking of a crystal, or even allowing the surface to become dry.

The stress which is transmitted and which causes the disruption of the material, is not the explosion nor the direct cause of the explosion, but merely the disturbance which releases the union between the atoms of the explosive compound, thus allowing them to re-combine, in a more stable form, with the resultant release of energy. This can be looked at as the distinction between the endothermic and the exothermic compounds. Endothermic compounds possess a large part of their energy in their structure and, therefore, release this energy, due to structure, instantaneously upon destruction of the form. This characteristic makes them effective as initiators of detonation. On the other hand, the exothermic

compounds require expenditure of energy for the destruction of their form and derive a larger proportion of their energy from the recombination of their elements in the more stable condition.

The speed of the detonation wave is controlled by the physical condition of the medium, in the same way as the rate of sound is determined by the physical constants. The violence of the reaction following the wave is dependent almost entirely upon the chemical nature of the material left by the wave, or more exactly, the products of detonation.

The distortion which brings about the breaking, carries a portion of the material forward and because of the intense pressure generated behind the wave, the backward movement of the medium is prevented. This phenomenon tends to increase the speed of the wave front. This effect explains the fact that the rate of detonation increases more rapidly with the increase of density, in an insensitive than in a sensitive explosive. The insensitive material must be distorted and moved forward to a greater extent, than the sensitive material, before breaking occurs. There are two factors acting to cause higher rate of detonation at higher densities:

(a) The increased rate of sound at higher densities,

(b) The effect of the distortion of the material. The forward movement of the material, due to the distortion of the detonation, differs from that produced by sound, by being a unidirectional movement. The molecules have collapsed and the energy for the continuation of the wave is furnished by the gases and heat liberated by the break-down or by the re-combination of the elements after the break-down.

From these facts, Carl presents the following formula for the straight line representing the rate of detonation:

$$y = (a + a')x + b$$

a - representing the constant by which the rate of sound increases with increased density;

a' - representing the constant by which the collapse of the molecule increases the rate through the explosive. Experimental evaluation of b has been found for various explosive detonating compounds and the results seem to follow the straight line predicted. Carl (4) says:

"In the acceptance of this breaking theory, the most outstanding quality of explosives is sensitivity. This quality can be most definitely correlated with the rate of detonation and that the sensitivity to detonation

is very definitely affected by the following factors:

(a) Perfect crystals and other perfectly elastic materials are the most susceptible or sensitive to detonation and propagate the wave with the closest adherence to the straight line curve.

(b) Materials which form long and complex molecules resist the initiation and propagation of detonation.

(c) Small amounts of impurities have a great effect on sensitivity.

(d) The condition of the surface of materials may decidedly influence their sensitivity to detonation.

(e) Liquids seem to resist detonation, due mainly to their lack of rigidity.

(f) Compounds may be classified as exothermic and endothermic and the sensitivity of the two are radically different. Both types of compounds show surface instability. The endothermic materials are the only types that possess the internal strain".

In conclusion, this theory states that the power of the shattering effect of explosives does not depend upon the rate of detonation. Nor does the total heat of explosion show the nature of the explosive. One must examine the heat of explosion from its basic cause; some comes

from heat of formation, the rest from the re-combination of the products of detonation.

Many people may not agree with several of the points brought out in this theory by Carl. One thing seems to be true though, and that is this theory does collect in one place, many of the problems and aspects of the theory of detonation. One fact to be gained from this theory is that a person undertaking fundamental research in this field, has some definite points to begin with. One can then either rule out parts of this theory as incompatible with experimental data, or accept them.

Strength of Detonators

The detonators generally manufactured today are designated as Nos. 6 and 8. Other grades are made only rarely and usually for special purposes. The figure designating the size of the detonator, refers to its strength as compared with that of standard detonators that contain mercury fulminate. The following tabulation shows the charges corresponding to the various original grades:

Grade No.	Charge in grams
1	0.30
2	0.40
3	0.54
4	0.65
5	0.80
6	1.00
6-1/2	1.25
7	1.50
8	2.00
9	2.50
10	3.00

These standard charges have been either (a) 80/20 mercury fulminate - potassium chlorate, (b) 90/10 mercury -

fulminate - potassium chlorate, or (c) 100 per cent mercury fulminate. The mixtures represented by (a) and (b) have been common, whereas (c) has been rare.

It is customary to define the initiating power (strength) of a detonator in terms of the test used. Thus, the strength of a No. 6 detonator may be defined as one that is not inferior in initiating power to a detonator containing 1 gram of a mixture of 80 per cent mercury fulminate and 20 per cent potassium chlorate.

Four common tests are employed for determining this strength.

1. TNT - iron oxide insensitive powder test.

Although time-consuming, this test is believed by some to be reliable. It is used in certain Government specifications for detonators.

2. Sand test

This test is more rapid and gives good reproducibility (11).

3. Lead-plate test

This test is the most rapid and is, therefore, used principally for control work. However, the results are hard to correlate as evidenced by the difficulty that has been experienced in establishing a set of standard

lead plates (21). The results may even be misleading as a measure of strength, because the size of the hole produced is profoundly influenced by factors such as the shape and diameter of the bottom of the detonator and the nature of confinement of the explosive charge within the detonator.

4. Small Trauzl lead-block test

This test is not widely used, although it gives a fair measure of the relative strength of a detonator.

Because it is a serious defect for a detonator to have less than its designated strength and an asset to have slightly greater strength, most detonators are made stronger than their designated grade. For example, many No. 6 detonators show a strength as determined by one of the above tests, equal to a No. 7 or even a No. 8 detonator.

TNT-Iron Oxide Insensitive Test

The procedure for this test is as follows: Different blends of TNT-iron oxide, each varying by one per cent of iron oxide, are carefully prepared by weighing the constituents, mixing, and repeatedly screening. The mixed powder is tamped uniformly into 1-1/2 - 4 inch

cartridges, each weighing 70 grams. These cartridges are then fired by the detonator under test, which is inserted in the usual manner in the end of the cartridge suspended vertically in air. The blends of TNT-iron oxide that produce 20 consecutive detonations and 20 consecutive failures, are determined. In addition, 20 trials are made for each intermediate blend. The iron oxide content of the corresponding blends is taken as a measure of the strength of the detonator. Generally, the same procedure is carried out with a standard detonator for comparison purposes. Inasmuch as it is claimed that weather conditions affect the results, it is best to make all the trials on the same day.

The Sand Test (11)

The lead-plate test, nail test, and others, all depend on the mechanical effects produced by unconfined detonators placed in certain definite positions relative to the material to be acted on. In the lead-block test, the detonator is closely surrounded by the lead, upon which it acts, but the results of comparisons obtained with this test fail to show that the test is a reliable one for determining the relative efficiencies of detonators.

In 1910, W. O. Snelling, then an explosives chemist of the Bureau of Mines, devised a direct method for testing the strength of detonators. This strength depends on the extent to which a hard, brittle material of uniform granulation, was pulverized by the explosion of the detonator charge. The detonator was placed in a suitable bomb, which was then partly filled with a given weighed quantity of ordinary, clean, dry sand of uniform granulation (20 to 40 mesh). The detonator was then fired and the degree of the resulting disintegration or pulverization of the sand was determined by removing the sand from the bomb and sifting it through a series of standard sieves. The total quantity of sand passing through the 40-mesh sieve varied with detonators of different commercial grades, but was remarkably uniform for detonators of the same grade.

Results from this test indicated that the method offered a convenient and accurate means of determining the relative strength of detonators, in spite of the fact that as it measured only the physical effects produced by the detonator, it appeared to be subject to most of the objections that have been advanced concerning many of the direct methods of testing.

The method of procedure is the same for testing

either electric detonators or ordinary detonators. The detonator is fired in approximately the center of a mass of 100 grams of the standard sand. After the explosion, the cover of the bomb is removed and the sand is emptied on to a large sheet of glazed paper. The electric detonator legs or the charred fuse, together with any large fragments of the copper shell, are rejected after any adhering sand has been removed from them, and the entire charge of sand is carefully sifted through a nest of sieves. The sand should not be rubbed with the hand, as such treatment would force through the sieve particles that would otherwise remain on the sieve. After the screening is complete, the separate fractions of the sand remaining in each sieve and in the bottom tray, are emptied onto small sheets of glazed paper, transferred separately to a weighing scoop, and weighed.

Many series of tests have been carried out on commercial detonators and it seems to be the best test for accurately measuring the detonating efficiency of a detonator. Even though you cannot apply directly any of the theories of detonation to this specific test and thus explain why it gives the results it does, one sees here why there have been so many varied tests used for detonators. This test today still is one of the most

reliable to give the answer to how efficient your detonator is in doing the job it has been designed for and that is complete detonation of the high explosive.

Lead Plate Test (12)

One of the early tests for evaluating efficiency of a detonator was the lead plate test and consists of firing a detonator while supported in a vertical position, its base resting on the center of a lead plate about 1-1/2 in. square by 3/16 in. thick. The appearance of the lead plate after the detonator is fired, furnishes a pictorial representation of the explosive action of the detonator charge. In the center of the plate, at the point of contact with the base of the detonator, there occurs a depression which is dependent for depth both upon the size and quality of the detonator. Radiating from this central depression or perforation, as the case may be, are numerous striations of fine dotted lines. These striations constitute the real index to the quality of the detonator and the explosive effect of its composition. Each dotted line is the result of a glancing blow inflicted by a single particle of the detonator shell.

The detonation of a good quality fulminate of mer-

cury charge bursts the shell wall into innumerable concentric rings, each of which in turn, shattered into numerous small fragments. As the quality of a fulminate of mercury detonator is lowered, the size of the shell fragments becomes larger, due to a less brusque action of the explosive charge, and the radial striations on the lead plate tend to be replaced by large pittings or splotches at irregular intervals on the face of the lead plate, these pittings being caused by the large fragments from the detonator case. If the detonator is of a very low quality, due to prolonged exposure to moisture, a defective grade of fulminate, a faulty mixture, or any other cause, so that it may be practically worthless for detonating powders, it will not shatter the shell into numerous small fragments, but will merely rupture the casing into a small number of broad strips. With this detonator, there are only a few broad, ribbon-like impressions radiating from an almost imperceptible depression where the detonator was in contact with the lead plate.

For convenience, the various graduations of quality for detonators are classified according to six different standards, which are in turn designated by the first six

letters of the alphabet. A being taken as 100% and F as 0% quality.

Table I shows a tabulated description of lead plates.

Classification	Quality	Indentation	Back side of plate	Radiation	Pittings
A	Good	Deep, often penetrating plate	Peeled	Fine, uniform	none
B	Good	do	do	do	Few, small
C	Fair	do	do	none	large deep
D	Bad	broad, shallow	none	none	do
E	Bad	small, shallow	none	none	do
F	Bad	small, shallow and covered by remains of shell	none	none	do

A set of standard lead plates are used, which represents the best judgment available from several years of both intensive experience with fulminate detonators and also extensive experimental work with other initiating compounds. Equipped with a set of these standards and a tabulated set of the above descriptions, one should be able to determine the quality of the detonators he is using.

If we look at the detonation of a high explosive as being brought about by the sudden impulse of the detonator, we see that two distinct factors enter into the development and application of this impulse. These are quickness or brisance, and strength. In a well-designed detonator, it is impossible to isolate these two factors.

Velocity of the chemical reactions involved is a function of the quickness, while the total volume of the gaseous combustion products is a function of the strength. Many compounds might be cited, which excel fulminate of mercury in strength but which are useless for detonating purposes; also many compounds might be mentioned which excel in quickness but which are vastly inferior to fulminate in initiating value.

The lead plate test is essentially a measure of quickness. Some of the interesting factors that effect the efficiency of a detonator, as shown by the lead plate tests, are size of charge, moisture, potassium chlorate content, [illegible] of shells, and hardness of detonator shells.

The element of quickness in fulminate of mercury detonators does not vary greatly with the size of the

charge. Therefore, the lead plate test does not indicate variation in weight of charges.

Moisture is universally admitted to be the greatest enemy of efficient detonators. An almost imperceptible moisture content is sufficient to impair seriously, the ability to detonate commercial explosives.

The shells of most commercial detonators bear a cone-like indentation which tends to improve the quality of the lead plate test (8) both by rendering the radiations finer and more uniform and by causing deeper indentation.

One of the few objections advanced against the lead plate test, was the belief that the quality of the test plate is greatly affected by the hardness or softness of the detonator shell. This was proved false by a series of tests using different hardness of the detonator shell itself.

The Trauzl Lead Block Test (12)

The trauzl test measures the comparative disruptive power of explosives when fired under moderate confinement. In making the test, equal weights of different explosives are confined in bore holes of definite dimensions, made in lead-blocks of prescribed character, by

means of a fixed quantity of stemming and when thus confined, are exploded by means of similar detonators. In this test, every factor is alike, except the character of the explosives which are being compared. The measure of the test is the volume by which the cavity in the block is increased because of the pressure exerted by the explosion under the degree of confinement to which the explosive is subjected by the quantity of stemming used, and the firmness with which this stemming is tamped.

Cylindrical lead blocks 200 mm. in diameter and 200 mm. in height are used. A bore hole 25 mm. in diameter and 125 mm. in depth is made centrally in the upper part of each block.

The bore hole in the lead cylinder to be used, is measured by means of water so as to ascertain its volume in cubic centimeters and cubic inches.

The explosive to be tested is placed in the opening and a No. 7 electric detonator is placed in the center of this charge. About 40 cc. of dry sand are poured into the bore hole and about the legs of the detonator and tamped with a tamping device. The charge is fired and the cavity in the block is then measured with water and

the increase in volume is ascertained with precision. The volume effect of just the detonator alone is determined on sand alone and its effect may be subtracted from the detonator being tested, thus giving the true value of the explosive that is charged in the Trauzl-lead block.

While these four tests that have been described are still used to measure the strength of detonators, explosive-testing engineers have long sought a satisfactory test for measuring quantitatively the initiating efficiency or strength of detonators. This was brought about by numerous developments and improvements in detonators during the past decade.

Most of the tests heretofore proposed for measuring the strength of detonators have had some serious deficiency. Generally, their value in measuring either absolute or relative initiating efficiency has been doubtful, while those few tests that were believed actually to evaluate relative initiating efficiency were difficult and cumbersome to perform.

It is a known fact that many explosives will detonate at different rates, depending upon the power or efficiency of the detonator used. For example, should a

detonator be too low in strength for the explosive used, the explosive will have an incomplete detonation and the resulting force of the explosion will be much lower than that weight of explosive should give. Therefore, it is of prime importance that a detonator possess at least the minimum initiating efficiency required for a complete detonation. It is much better to use an oversized detonator and insure enough strength for the highest order detonation possible.

Toward this end of getting a satisfactory initiating efficiency test for detonators, the minature-cartridge test was devised. This test is based on the fundamental and generally accepted concept that the ability of a detonator to initiate an insensitive explosive constitutes the best means of measuring its initiating efficiency. To represent a wide range of insensitive explosives, various mixtures of TNT iron oxide were selected for the initial study. The extent of detonation produced in the insensitive explosive is measured by the weight of sand crushed in a Bureau of Mines sand bomb. The miniature cartridge consists, essentially of a 5-gram charge of a carefully controlled TNT-iron oxide mixture in a small paper cup having an inside diameter of

one-half inch. The experimental technique thus combines the advantageous features of the sand test and the TNT-iron oxide insensitive powder test. A unique operation embodied in the miniature cartridge test is the subtraction of a detonator "blank". This achieves a measurement of the actual resultant effect of the detonator in producing a greater or lesser degree of detonation in an insensitive explosive.

The important considerations, not heretofore sufficiently emphasized in detonator tests, were experimentally confirmed and incorporated in this test.

The first of these is the fact that the packing density of an insensitive explosive, as exemplified by a TNT-iron oxide mixture, must be carefully controlled. Within certain limits, as the packing density of a TNT-iron oxide mixture increases, its explosive power, as measured by its sand crushing capacity, decreases rapidly. Packing density was kept within .94±.02 gram per cubic centimeter.

The second one was that insensitive explosives are capable of all degrees of partial detonation, depending on the initiating efficiency of the detonator used.

The technique of the simplified routine test consists, briefly, of loading a 5-gram charge of a homogeneous TNT-iron oxide mixture into a carefully made paper cartridge 1/2 inch inside diameter and 2-3/4 inches long. The packing density is constant, and the detonator is inserted to such a depth as to produce maximum initiation. The miniature cartridge thus assembled, is fired in the center of 1,000 grams of the standard sand in a steel bomb 3 inches inside diameter. The crushed sand, which passes through a No. 30 U.S. standard series screen, represents the sand pulverized by the TNT-iron oxide and the detonator. From this value is subtracted the detonator blank, which is obtained by similarly firing a miniature cartridge containing 5 grams of pure iron oxide and the detonator. The value of crushed sand thus derived, represents the initiating efficiency of the detonator. This initiating efficiency is then compared relatively with that of a suitable reference detonator. By the unique operation of subtraction of the detonator blank, the miniature-cartridge test incorporates the principle that the desired measurement is not the force of the detonator itself, but the resultant effect of the detonator in producing a greater or lesser degree of

detonation in an insensitive explosive.

Fuse Detonators

Since the time of Nobel, fuse detonators have had an important place in the field of explosives. They are commonly made in the form of copper, copper alloy, or sometimes aluminum tubes about 1/4 inch in diameter and approximately 1-1/2 to 2 inches in length, with one end closed (13). The closed end contains the pressed charge of initiating explosive, whereas the open portion is intended to receive the end of a length of safety tubes.

The metal casing of the detonator is commonly called the shell and is made by stamping, first a cup from a piece of flat copper. After annealing, the cup is drawn to the desired thickness and length in a battery of shell-drawing machines. (14)

Fuse detonators containing inner reinforcing capsules, usually made of copper or copper alloy, have come into wide use. These confining mediums increase the mechanical strength of the detonator, thereby decreasing the sensitivity to shock and impact; they also increase the degree of confinement and aid in focusing the detonation wave, both of which increase the initiating power of the detonator. These confining capsules have a cup-

like appearance, with a hole in the center of the bottom, through which the spit of the safety fuse or the flash from the ignition charge may be communicated to the remainder of the charge.

For many years the initiating explosives in fuse detonators, comprised a single charge of mercury fulminate or one of the fulminate-chlorate mixtures. The majority of modern detonators contain compound charges in super-imposed layers, frequently called wafers. These compound charges serve the same purpose as mercury fulminate, with the following advantages: the detonators are more economical, just as efficient, and less dangerous to manufacture and use.

To increase the confinement of the explosive charges, and hence to improve the explosive power, base and priming charges usually are loaded into the shells under pressure. This is a hazardous operation and is performed by remote control in hydraulic presses placed behind heavy, protective barricades. The pressures must be controlled carefully to prevent detonation of the charge. Pressures of 35 to 250 pounds per detonator (corresponding to approximately 950 to 6,800 p.s.i.) have been employed. Many charges substituted for mercury fulminate

So modern compound detonators can withstand greater pressures; mercury fulminate has been reported to detonate at an average pressure of 264 pounds per detonator, whereas hexanitromannite did not detonate at a pressure of 500 pounds.

Electric Detonators

Instantaneous electric detonators essentially are sealed fuse detonators, having an electrical system for igniting the explosive charge. The latter function is performed by a short length of fine electric filament wire embedded in a portion of the explosive charge within the detonator. When the filament wire, more frequently called the bridge wire, is brought to incandescence by the passage of an electric current through it, the following sequence of events occur: The portion of the explosive charge in contact with the bridge wire, which is usually the ignition charge, burns or flashes. This generation of heat develops detonation of the priming charge, which in turn imparts detonation to the base charge. The consequent bursting of the detonator shell, providing a combination of thermal and mechanical impulses, bring about the detonation of the main charge of explosive.

The high resistance, small-diameter bridge wire is probably the most important item of construction in an electric detonator. The properties desired in an ideal resistance wire have been difficult to attain: It must be corrosion-resisting, have relatively high tensil strength, have a small resistance change as the temperature is increased, must be constant in electrical properties, and should have low comparative cost. A constant search has been made in recent years to find better alloys for use as bridge wires.

These alloys have generally contained platinum as the basic metal. One of the most widely used has been made of 80% platinum and 20% iridium. It approaches the above required physical properties, but is rather costly. Another platinum alloy that has been used recently and that has higher tensile strength, in addition to being cheaper per unit length, is composed of 80% Pt., 15% Rhodium and 5% Ruthenium. A less widely used and less expensive alloy is nichrome, of which the nominal analysis is 60% Ni, 15% Chromium and 25% iron.

A typical resistance wire used for bridge wires may have a diameter of 0.0016 inch and a length of 0.12 inch. Depending on the material from which it is made,

it may have a resistance of 200 to 400 ohms per foot and a tensile strength of 100,000 to 300,000 pounds per square inch. A standard roll of such wire, weighing 1 pound, will contain 100,000 to 200,000 feet.

In the electric detonators the four modes of making contact between the bridge wire and the ignition charge, are:

1. The bridge wire may simply be embedded in the loose ignition charge. This is often referred to as the bridge plug type.

2. The bridge wire may be dipped into a viscous suspension of the ignition charge in a solvent and then dried to form an adhering pellet, commonly called a bead. A coating of nitrocellulose often is applied to the outside of the bead to provide a protective skin.

3. The matchhead type of ignition is constructed as follows: Two strips of metal foil, soldered to the end of the leg wires, are separated by a flat strip of insulating material, such as paper, and connected across their ends by a short length of bridge wire soldered to each. By dipping the bridge wire portion of this assembly into a suspension of the ignition charge in a volatile liquid, followed by drying to remove the liquid,

the bridge wire becomes surrounded with a rigid globule of the ignition charge.

4. The cavity type of ignition comprises a saucer-like, cylindrical, or prismatic cavity in one end of the bridge plug. The bridgewire lies within the cavity and is soldered across the ends of the leg wires, which do not project out of the cavity. The ignition composition, in wet plastic form, is then inserted into the cavity, the surface smoothed, and the composition dried.

Compound electric detonators are analogous to compound fuse detonators; a single charge has been replaced by a compound charge of two or three individual explosive materials. One material frequently may function or serve as both ignition charge and priming charge; less frequently, one material may function or serve as all three charges--ignition, priming, and base. An example of a compound electric detonator with two charges is that described by Burrows (15), consisting of a base charge of a mixture of 80% mercury fulminate and 20% potassium chlorate and an ignition composition of basic lead styphnate.

Electric detonators are well sealed to make them [illegible]

impervious to moisture and to hold and guard the fragile bridge wire. They have good water-resisting characteristics and accordingly, are used in wet blasting operations where conditions are not too severe. However, for underwater blasting, where the water pressure may be high or the time of immersion may be long, special submarine or waterproof electric detonators are used. The distinguishing feature of submarine electric detonators is the longer shell, with an extra quantity of waterproofing material employed.

The usual type of seal used is a composite one. The bridge plug is made to fit rather tightly and first inserted into the loaded shell, followed by pouring a viscous charge of asphaltic material around it to harden. Such a seal compels the use of relatively long shells and has the additional disadvantage that it is not completely satisfactory when exposed to extreme temperatures. At higher temperatures, the asphalt may melt, mix with the ignition or priming charge, and desensitize it, thus causing the detonator to fail to function. At low temperatures the asphalt may contract and crack, thus providing an entry for moisture when the detonator is exposed at normal temperatures. In this type of seal the asphaltic material is primarily

intended as the waterproofing substance.

Recently a novel single seal has come out, consisting of a doubly crimped synthetic rubber plug. This seal has permitted a much shorter shell to be used; also single incombustible seals of glass or of a suitable metal, such as copper, brass, or aluminum, have been proposed. A thermoplastic resin seal, consisting of one of the synthetic organic polymers, such as methyl methacrylate, ethyl cellulose, cellulose acetate, or the vinyl halide polymers, also have been developed.

Delay Electric Detonators

Just as an electric detonator may be visualized as a fuse detonator, with a bridge wire assembly and seal, a delay electric detonator may be imagined as an electric detonator with a delay element, or powder train inserted between the bridge wire assembly and the explosive charge. Delay detonators fire at definite short intervals after the electric circuit is closed; these intervals range from approximately 1 to 20 seconds, according to the delay of the detonator. By using delay electric detonators, it is possible, with one application of current, to fire a series of shots in rotation or succession, at short and reasonably reproducible

intervals of time.

Delay electric detonators have been improved remarkably during the last 10 years; modern delay detonators are less bulky, have more reliable firing characteristics, may be used under water and are more easily manufactured.

There are two principle types of delay electric detonators, those having a vent for the escape of gases, and those that are ventless. Successful detonators of the latter type are a recent development. Passage of an electric current through the bridge wire brings it to incandescence and flashes the ignition material. The flame thus produced sets fire to the delay powder, which is pressed into a metal tube. The longer the delay powder train, the longer will be the delay time of the detonator. When the delay powder has burned to the opposite end of the tube, it ignites the priming charge, which then fires the detonator.

The time required for the delay powder to burn is highly important, for if the delay powder burns more rapidly in one detonator than in other detonators of the same delay period, the first detonator will fire prematurely.

Delay electric detonators with a vent have a delay composition that produces gases upon burning. If these gases were not allowed to escape, they would cause the pressure to build up, which would accelerate the rate of burning of the delay powder and cause premature firing of the detonator. Vented delay detonators have several disadvantages. They are not generally satisfactory for use under extreme heads of water because the vent provides a possible point of entry for water. Accidental plugging of the vent when the detonator is fired, may cause a premature explosion. Furthermore, escape of hot gases may cause the charge to burn and this may develop into an attendant premature detonation.

Because of the disadvantages of the vented type delay detonators, serious efforts have been made to develop a satisfactory ventless delay detonator. The problem has narrowed to finding a delay composition which, when it burned, would do so at a uniform rate and would produce an exothermic chemical reaction without the evolution of gases. A composition of 85% barium peroxide and 15% selenium was found and subsequently used in a commercial delay electric detonator after it was found successful. This type of detonator is more

suitable for use under water than the vented type.

The wartime necessity for manufacturing detonators in one part of the world for use in another, imposed the problem of constructing detonators to function satisfactorily in extremes of climate.

Conclusion

To try and cover all phases of detonators and detonation, from the commercial and military standpoint, would be an endless job. The two theories of detonation covered represent both an early and a more recent theory; still some of the same problems are left unsolved. It is necessary, therefore, that a continued study be made in the theory of detonation in order to be certain the detonators that are designed and built today do the best job. Every high order explosive must be detonated and the more knowledge we have on the efficiency of the various types of detonators, the more certain we are that the maximum power is being obtained from the explosive.

In the development of new weapons, all the scientific skill and effort used to design and build the weapon will have been wasted if the small, almost insignificant

detonator, does not function at the proper time and in the proper manner. Along with development of better explosives must come the development of better, more efficient detonators.

Bibliography

(1) Investigations of Detonators and Electric Detonators, Clarence Hall and Spencer P. Howell, Bur. Mines Bul. No. 59.

(2) Naval Ordnance 1937.

(3) Explosives and Their Power, Berthelot, M., 1892.

(4) The Breaking Theory of Detonation, Leroy Carl, Jour. of Franklin Institute, July-Aug.-Sept. 1940.

(5) Reports of Investigation, Series 2923, April 1929, Department of Commerce, Bur. of Mines.

(6) "Elements of Ordnance", Lt. Col. Hayes, 1938, John Wiley and Sons, N. Y.

(7) "The Physics of Crystals", 1928, McGraw-Hill Publ. Co., pp. 59, 63.

(8) Journal of Applied Physics, 9, p. 519, Aug. 1938.

(9) "Theories of Organic Chemistry", Henrich, 1922, John Wiley and Co., N. Y.

(10) Chem. and Metallurgical Engineering, Vol. 26, No. 24, 1922.

(11) Bureau of Mines Technical Paper 125.

(12) Bureau of Mines Bulletin 15.

(13) DuPont de Nemours and Co., Blaster's Handbook, 11th ed., 1942.

(14) Holland, C. T., Safe Practice in the Manufacture and Testing of Detonators, Commonwealth of Pa., Safe Practice Bull. 33, 1941.

(15) Burrows, L.A., Electric Blasting Initiator, U.S. Patent 2,086,530, July 13, 1937.

(16) Structural Features of Typical American Commercial Detonators, Bur. of Mines Rept. of Investigation, 3696, 1943.

(17) The Lead-Plate Test as Applied to Detonators, Chem. and Met. Eng. Vol. 26, 1922, by Grotta.

(18) Investigation of Detonators and Electric Detonators, Bur. of Mines Bull. 59, 1913, Hall, C.

(19) Physical Testing of Explosives at the Bureau of Mines Explosives Experiment Station, Bruceton, Pa., Bur. of Mines Bull. 346, 1931, Monroe, C.E.

(20) Influence of Density of Packing Upon Explosibility of Ammonium Nitrate, Army Ordnance, Vol. 4, No. 23, Sherrick, J.L.

(21) The Energy of Explosives, Proc. Eng. Soc. West Pa. Vol. 28, 1912, Snelling, W.O.

(22) Initial Priming Substances for High Explosives, Bur. of Mines Tech. Paper 162, 1917, Taylor, C.A. and Cope, W.C.

(23) Photographic Study of Detonation, Ind. Eng. Chem. Vol. 36, pp. 79-85, 1944.

(24) Measurement of the extent of Detonation in the Testing the Initiating Efficiency of., Bur. of Mines Tech. Paper 677, 1945.

(25) Characteristics of Detonation, J. Applied Physics, Vol. 10, pp. 344-59, 1939.

(26) Initiating Efficiency of Detonators, Ind. Eng. Chem. June, 661-666, 1945.

(27) Explosion Waves and Shock Waves vs. Shock Wave and Explosion Products from Detonating Solid Explosives, Proc. Royal Society, London, A 163, 575-92 1937, Payman, W. and Woodhead, D.W.

(28) Solid Reaction and Detonation, Sci. J. Soc. 5, 22-44, 1935, Garner, W.E.

(29) The Mechanism of the Initiation and Propagation of Detonation in Solid Explosives, Proc. Royal Soc. London, A 138, 98-116, 1932, Taylow, W. and Weale, A.

(30) The Nature of Detonation, Army Ordnance 10:3721, 5 1924, Olsen, F.

(31) "Explosive Materials", M. Berthelot, D. Van Nostrand, 1883, N. Y.

(32) "High Explosives", Glover, 1918, Cheek Press, London.

(33) "Explosives and Their Power", Berthelot, 1892, J. Murray, London.

(34) "Explosives", Marshall, J. and A. Churchill Ltd., London.

(35) "Elements of Ordnance", Lt. Col. Hayes 1938, John Wiley and Sons, N. Y.

(36) "The Physics of Crystals", 1928, McGraw-Hill Book Co., N. Y.

VITA

[illegible] [illegible] [illegible] was born in [illegible] [illegible], [illegible], the son of [illegible] and [illegible], [illegible] [illegible], on the [illegible] of [illegible], [illegible].

[illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] from [illegible] to [illegible], [illegible] [illegible] [illegible] [illegible] in [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible], [illegible] [illegible] [illegible] [illegible] [illegible], [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible].

DATE DUE

24 AP'51			

The
C18

Thesis
C188 Calhoun 13245
Detonators and detonation.

thesC188
Detonators and detonation.
3 2768 002 08445 1
DUDLEY KNOX LIBRARY